

# STERILE NEUTRINOS

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## ABSTRACT

A simultaneous understanding of the results of the LSND experiment indicating  $\nu_\mu - \nu_e$  oscillation together with other evidences for neutrino oscillations from solar and atmospheric neutrino data seems to require the existence of at least one sterile neutrino. One can also give other plausible astrophysical arguments that seem to require light sterile neutrinos. A major theoretical challenge posed by their existence is to understand why they are so light. A scenario is presented where one assumes a parity doubling of the standard model with identical matter and gauge content. The neutrinos of the parity doubled (mirror) sector are light for the same reason that the known neutrinos are light and since they do not couple to the known  $W$  and  $Z$  bosons, they can be identified with the sterile neutrinos. Some of the implications and possible tests of this hypothesis are mentioned.

## 1. Why we may need a sterile neutrino?

The announcement by the Super-Kamiokande collaboration<sup>2</sup> of the evidence for neutrino oscillation (and hence nonzero neutrino mass) in their atmospheric neutrino data is a major milestone in the search for new physics beyond the standard model. In addition to the Super-Kamiokande atmospheric neutrino data, there are now strong indications for neutrino oscillations<sup>1</sup> from the five solar neutrino experiments (Kamiokande, Homestake, Gallex, Sage and Super-Kamiokande<sup>3,4</sup>), other atmospheric neutrino observations<sup>5,6</sup> and the direct laboratory observation in the LSND experiment<sup>7</sup>. To explain all three evidences for neutrino oscillations, three different mass differences ( $\Delta m^2$ ) are needed. The atmospheric neutrino data requires  $\Delta m_{\mu-X}^2 \sim 3 \times 10^{-4} - 7 \times 10^{-3} \text{ eV}^2$  whereas the solar neutrino data prefers either  $3 \times 10^{-6} - 7 \times 10^{-6} \text{ eV}^2$  or  $\sim 10^{-10} \text{ eV}^2$  depending on whether the solution arises via the MSW mechanism or via oscillation in vacuum<sup>8</sup>. The LSND data on the other hand prefers  $0.2 \text{ eV}^2 \leq \Delta m_{e\mu}^2 \leq 2.0 \text{ eV}^2$  with  $\Delta m^2$  as high as  $10 \text{ eV}^2$  also in the allowed range. The LSND observations need to be corroborated by either KARMEN<sup>9</sup> or the proposed BooNE experiment. If however, we take the LSND experiment seriously, we have a crisis for the three neutrino picture since with the three known neutrinos one can get only two independent  $\Delta m^2$ 's. A simple solution to this crisis is to adopt the proposal<sup>10</sup> that an ultralight fourth neutrino, to be called the sterile neutrino exists<sup>11</sup>. For the uninitiated a sterile neutrino is defined as one whose interaction strength with standard model particles (such as the  $W, Z$  etc) is much weaker than that of the usual weak interaction. The reason for this is the discovery at LEP and

SLC that only three neutrino species couple to the Z-boson. It is the goal of this talk to discuss other motivations for sterile neutrinos and then discuss possible theoretical scenarios for the sterile neutrinos after a brief discussion of how its introduction solves the neutrino puzzles.

## 2. Scenarios for solving the neutrino puzzles

In the presence of this extra neutrino species ( $\nu_s$ ), one can construct several scenarios for solving the three neutrino puzzles<sup>10,12,13,14</sup>. In the original paper introducing the sterile neutrino to solve the neutrino puzzles<sup>10</sup>, it was proposed that the solar neutrino puzzle is solved via the oscillation of the  $\nu_e$  to  $\nu_s$  using the MSW mechanism<sup>15</sup> and the atmospheric neutrino puzzle is solved via the  $\nu_\mu - \nu_\tau$  oscillation with maximal mixing. The solar neutrino puzzle fixes the  $\Delta m_{e-s}^2 \simeq (0.35 - .75) \times 10^{-5} \text{ eV}^2$ , whereas the atmospheric neutrino puzzle implies that  $\Delta m_{\mu-\tau}^2 \simeq 10^{-3} \text{ eV}^2$ . This gives a picture where the  $\nu_s$  and  $\nu_e$  are close by in mass with nearly zero mass and the  $\nu_\mu$  and  $\nu_\tau$  are nearly degenerate in mass. The masses of the  $\nu_\mu - \nu_\tau$  system is determined by the LSND experiment  $m_{\nu_2} \simeq m_{\nu_3} \simeq \sqrt{\Delta m_{LSND}^2}$ . If the universe has a hot component in its dark matter, as some recent analyses suggest<sup>16</sup>, then this requires the  $\nu_\mu$  and  $\nu_\tau$  masses to be each 2-3 eV implying that in LSND and KARMEN<sup>9</sup> one should observe a  $\Delta m^2 \simeq 4 - 9 \text{ eV}^2$ . This point about hot dark matter has however become controversial<sup>17</sup> in view of recent indications that the total mass density of the universe may be considerably less than critical<sup>18</sup>, an assumption that was used in concluding that the universe has 20% HDM.

This scenario is testable in the SNO<sup>19</sup> experiment once they measure the solar neutrino flux ( $\Phi_\nu^{NC}$ ) in their neutral current data and compare with the corresponding charged current value ( $\Phi_\nu^{CC}$ ). If the solar neutrinos convert to active neutrinos, then one would expect  $\Phi_\nu^{CC}/\Phi_\nu^{NC} \simeq .5$ , whereas in the case of conversion to sterile neutrinos, the above ratio would be nearly  $\simeq 1$ .

A second scenario advocated in Ref.<sup>13</sup> and in <sup>14</sup> suggests that it is the atmospheric  $\nu_\mu$ 's that oscillate into the sterile neutrinos whereas the solar neutrino oscillation could be involving either active or sterile ones depending on how many sterile neutrinos one postulates. The present atmospheric neutrino data cannot distinguish between the  $\nu_\tau$  and  $\nu_s$  as the final oscillation products. There is however an interesting suggestion<sup>20</sup> that monitoring the pion production via the neutral current reaction  $\nu_\tau + N \rightarrow \nu_\tau + \pi^0 + N$  (which is absent in the case of sterile neutrinos) can help in distinguishing between these two possibilities. Another possible way to distinguish the  $\nu_\mu - \nu_\tau$  oscillation possibility from the  $\nu_\mu - \nu_s$  one for the atmospheric case may be to observe dips in the zenith angle distribution of the data due to matter oscillation in the earth for higher energy neutrinos<sup>21</sup>.

There is yet a third scenario according to which<sup>24</sup> both solar and atmospheric neutrino oscillations involve the active neutrinos whereas the LSND data is an indirect

oscillation that goes via the sterile neutrino which may have a mass of  $\sqrt{\Delta m_{LSND}^2}$ .

A possible mass matrix for the first case is<sup>23</sup>:

$$M = \begin{pmatrix} \mu_1 & \mu_3 & 0 & 0 \\ \mu_3 & 0 & 0 & \epsilon \\ 0 & 0 & \delta & m \\ 0 & \epsilon & m & \pm\delta \end{pmatrix}. \quad (1)$$

Solar neutrino data requires  $\mu_3 \ll \mu_1 \simeq 2 \times 10^{-3} \text{ eV}$  and  $\epsilon \simeq .05m$ . In the case with the negative sign in the 44-entry, the  $\Delta m^2$  in the atmospheric data as well as the mixing in the LSND oscillation are linked to one another.

Finally, one has to ensure that all the new light particles introduced to explain the sterile neutrino do not spoil the success of big bang nucleosynthesis which cannot tolerate more than 1.5 extra neutrinos<sup>28</sup>. The contribution of a sterile neutrino is governed by its mass difference -squared and mixing with the normal neutrinos. For instance, the contribution of a sterile neutrino is suppressed<sup>29</sup> as long as the following inequality is satisfied:

$$\Delta m^2 \sin^4 2\theta \leq 3 \times 10^{-6} \text{ eV}^2 \quad (2)$$

Any theoretical model must respect this constraint.

### 3. Other motivations for the sterile neutrino

There are several astrophysical observations whose understanding becomes easier if one assumes the existence of a sterile neutrino. The first example is a proper understanding of the heavy element abundance in the universe. A very plausible site for the production of heavy nuclei in the universe appears to be the hot neutron rich environment surrounding type II supernovae. The first road block that this proposal runs into arises from the fact that there are also hot neutrinos ( $\nu_e$ 's) surrounding the supernova core (indigenous as well as oscillation generated from  $\nu_\mu$ 's) which have the effect of suppressing this process by reducing the neutron fraction via the reaction  $\nu_e + n \rightarrow e^- + p$ . It has recently been shown<sup>24</sup> that the introduction of the sterile neutrino seems to alleviate the problem by providing a “sucking” mechanism for the “bad” neutrinos into sterile neutrinos.

A second, albeit speculative motivation for the sterile neutrinos comes from the observed pulsar velocities (of about 500 to 100 km/sec.), for which there seems to be no convincing astrophysical explanation. One suggestion<sup>25</sup> based on the idea of neutrino oscillation is that in the presence of large magnetic fields, matter induced oscillations of the neutrinos will become asymmetric due to the presence of  $\mathbf{k} \cdot \mathbf{B}$  terms in the resonance condition. Thus the neutrinos emerging on one side would have a larger momentum than those on the other side, thereby giving a momentum to the pulsar at its birth. However, for this mechanism to work one needs a neutrino with

mass in the 100 to 300 eV range. Such a large mass would be unacceptable for the  $\nu_{\mu,\tau}$  since that would overclose the universe. The sterile neutrinos on the other hand could have such masses without giving  $\Omega_m \geq 1$  since their interaction with known matter is ultraweak and that makes them decouple above  $T = 200$  MeV (where  $T$  is the temperature of the universe); the subsequent annihilation of known particles heats up the universe of the known particles thereby reducing the concentration of the sterile neutrinos at the present time. It is not very difficult to reduce their present density by 10-20, thus making it possible to have their mass be higher. Thus if matter enhanced neutrino oscillation is identified as the only way to account for observed pulsar velocities, that would provide indeed a very strong motivation for the sterile neutrinos.

A third motivation of similar speculative nature has to do with an understanding of the observed diffuse ionization in the milky way and other galaxies. A possible understanding of the various properties of the observed ionization (such as its large scale height  $\sim 700$  pc and uniform distribution etc.) suggests that they could be caused by the radiative decay of some species of heavy neutrinos<sup>26</sup>. But energetics of the problem require that the decaying neutrino must have mass of 27.4 eV. Any of the active neutrinos with a mass of this type would lead to  $\Omega_m = 1$  in contradiction with recent indications. On the other hand, the sterile neutrino is free of such mass constraints and it has been recently shown<sup>27</sup> how a sterile 27.4 eV neutrino could provide a combined resolution of both the diffuse ionization problem along with the other neutrino puzzles.

#### 4. Mirror universe theory of the sterile neutrino

If the existence of the sterile neutrino becomes confirmed say, by a confirmation of the LSND observation of  $\nu_\mu - \nu_e$  oscillation or directly by SNO neutral current data to come in the early part of the next century, a key theoretical challenge will be to construct an underlying theory that embeds the sterile neutrino along with the others with appropriate mixing pattern, while naturally explaining its ultralightness.

It is clear that if a sterile neutrino was introduced into the standard model, the gauge symmetry does not forbid a bare mass for it implying that there is no reason for the mass to be small. It is a common experience in physics that if a particle has mass lighter than normally expected on the basis of known symmetries, then it is an indication for the existence of new symmetries. This line of reasoning has been pursued in recent literature to understand the ultralightness of the sterile neutrino by using new symmetries beyond the standard model.

We will focus on the recent suggestion that the ultralightness of the  $\nu_s$  may be related to the existence of a parallel standard model<sup>30,13,31</sup> which is an exact copy of the known standard model (i.e. all matter and all gauge forces identical). excitations.

<sup>a</sup> The mirror sector of the model will then have three light neutrinos which will not couple to the Z-boson and would not therefore have been seen at LEP. We will call the  $\nu'_i$  as the sterile neutrinos of which we now have three. The lightness of  $\nu'_i$  is dictated by the mirror  $B' - L'$  symmetry in a manner parallel to what happens in the standard model. The two “universes” communicate only via gravity or other forces that are equally weak. This leads to a mixing between the neutrinos of the two universes and can cause neutrino oscillation between  $\nu_e$  of our universe to  $\nu'_e$  of the parallel one in order to explain for example the solar neutrino deficit.

At an overall level, such a picture emerges quite naturally in superstring theories which lead to  $E_8 \times E'_8$  gauge theories below the Planck scale with both  $E_8$ s connected by gravity. For instance, one may assume the sub-Planck GUT group to be a subgroup of  $E_8 \times E'_8$  in anticipation of possible future string embedding. One may also imagine the visible sector and the mirror sector as being in two different D-branes, which are then necessarily connected very weakly due to exchange of massive bulk Kaluza-Klein excitations.

As suggested in Ref.<sup>30</sup>, we will assume that the process of spontaneous symmetry breaking introduces asymmetry between the two universes e.g. the weak scale  $v'_{wk}$  in the mirror universe is larger than the weak scale  $v_{wk} = 246$  GeV in our universe. The ratio of the two weak scales  $\frac{v'_{wk}}{v_{wk}} \equiv \zeta$  is the only parameter that enters the fit to the solar neutrino data. It was shown in Ref.<sup>30</sup> that with  $\zeta \simeq 20 - 30$ , the gravitationally generated neutrino masses<sup>33</sup> can provide a resolution of the solar neutrino puzzle (i.e. one parameter generates both the required  $\Delta m^2_{e-s}$  and the mixing angle  $\sin^2 2\theta_{e-s} \simeq 10^{-2}$ ).

There are other ways to connect the visible sector with the mirror sector using for instance a bilinear term involving the righthanded neutrinos from the mirror and the visible sector. An  $SO(10) \times SO(10)$  realization of this idea was studied in detail in a recent paper<sup>34</sup>, where a complete realistic model for known particles and forces including a fit to the fermion masses and mixings was done and the resulting predictions for the masses and mixings for the normal and mirror neutrinos were presented. In this model, the fermions of each generation are assigned to the  $(\mathbf{16}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{16}')$  representation of the gauge group. The  $SO(10)$  symmetry is broken down to the left-right symmetric model by the combination of  $\mathbf{45} \oplus \mathbf{54}$  representations in each sector. The  $SU(2)_R \times U(1)_{B-L}$  gauge symmetry in turn is broken by the  $\mathbf{126} \oplus \overline{\mathbf{126}}$  representations. These latter fields serve two purposes: first, they guarantee automatic R-parity conservation and second, they lead to the see-saw suppression for the neutrino masses. The standard model symmetry is then broken by several **10**-dim. Higgs fields. Using the charged fermion masses and mixings as inputs, we obtain the following absolute values of the neutrino masses (in eV's):  $m_{\nu'_\tau} = 90.56, m_{\nu'_\mu} = -90.56, m_{\nu'_e} = 0.0034, m_{\nu_\tau} = 1.51, m_{\nu_\mu} = -1.509, m_{\nu_e} = 0.001$ . The squared mass differences (in eV<sup>2</sup>) are  $\Delta m^2_{e-s} = 9.9 \times 10^{-6}$ ,  $\Delta m^2_{\mu-\tau} = 0.003$  and  $\Delta m^2_{e-\mu} = 2.27$ , where the numbers are given in eV<sup>2</sup>. The neutrino mixing matrix  $O^\nu$

<sup>a</sup>For alternative theoretical models for the sterile neutrino, see Ref.<sup>32</sup>

of the six neutrinos in the basis  $(\nu_e, \nu_\mu, \nu_\tau, \nu'_e, \nu'_\mu, \nu'_\tau)$  is approximately given as,

$$O^\nu = \begin{pmatrix} -0.99 & 0.037 & 0 & 0.039 & -0.00025 & 0 \\ -0.031 & -0.85 & -0.52 & -0.00072 & 0 & 0 \\ 0.019 & 0.525 & -0.85 & -0.00043 & 0 & 0 \\ -0.042 & 0.0014 & 0.00071 & -0.999 & 0.0062 & 0 \\ 0 & 0 & 0 & -0.0053 & -0.850 & -0.525 \\ 0 & 0 & 0 & 0.0032 & 0.52 & -0.85 \end{pmatrix} \quad (3)$$

Combining this with the mixing angle for the charged leptons, we obtain the final mixing matrix among the four neutrinos which serves the desired purpose of fitting all the neutrino oscillation data.

Turning now to the consistency of our model with big bang nucleosynthesis (BBN), we recall that present observations of Helium and deuterium abundance can allow for as many as 4.53 neutrino species<sup>28</sup> if the baryon to photon ratio is small. In our model, since the neutrinos decouple above 200 MeV or so, their contribution at the time of nucleosynthesis is negligible (i.e. they contribute about 0.3 to  $\Delta N_\nu$ .) On the other hand the mirror photon could be completely in equilibrium at  $T = 1$  MeV so that it will contribute  $\Delta N_\nu = 1.11$ . All together the total contribution to  $\delta N_\nu$  is less than 1.5.

There may be another potentially very interesting application of the idea of the mirror universe. It appears that there may be a crisis in understanding the microlensing observations<sup>35</sup>. It has to do with the fact that the best fit mass for the 14 observed microlensing events by the MACHO and the EROS group is  $0.5M_\odot$  and it appears difficult to use normal baryonic objects of similar mass such as red dwarfs or white dwarfs to explain these events, since they lead to a number of cosmological and astrophysical problems<sup>36</sup>. Speculations have been advanced that this crisis may also be resolved by the postulate that the MACHOs with  $0.5M_\odot$  may be mirror stars<sup>37,38</sup> which would then have none of the difficulties that arise from the white dwarf or other interpretations.

In conclusion, if the LSND result stands the test of time, an ultralight sterile neutrino would be required to understand all neutrino data. Combined with other astrophysical arguments such as those based on supernova r-process nucleosynthesis, for example, it would appear that future developments in particle physics may very well require that we build models beyond standard unification framework that incorporate light sterile neutrinos. An interesting class of models that lead to a naturally light sterile neutrino postulates mirror matter and mirror forces. The existing MACHO and EROS data on microlensing events may be providing the first indications in favor of the existence of mirror matter since the observed MACHOs with average mass of around half a solar mass may find a more satisfactory explanation in terms of compact near solar mass objects built from mirror matter rather than those from ordinary matter. On the theoretical front, it is possible to construct fully grand unified models for mirror matter using the  $SO(10) \times SO(10)$  or  $SU(5) \times SU(5)$  group.

The recent ideas on D-branes embedded in higher dimensional space also naturally lead to mirror like pattern for particles and forces.

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